Halo and Sub-Halo Finding in Cosmological N-body Simulations

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Cosmological N-body Simulations

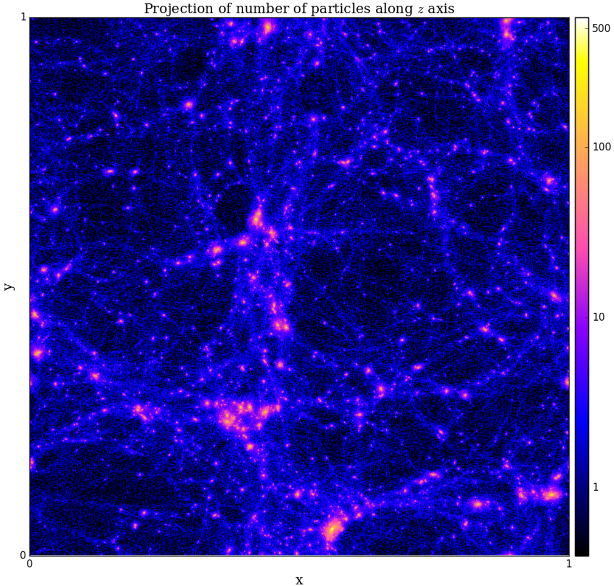
- N-body simulations are simulations of the motion of particles under the influence of physical forces.
- Focus on collisionless dark matter particles:
  - hypothetical type of matter
  - the only significant interaction between the particles is via gravity

Cosmological N-body Simulations

- After some time, the particles will clump together. Such gravitationally bound objects are called *halos*.
- Halos themselves may contain self-bound objects, called *subhalos*.
- The identification of halos and subhalos is an important tool for problems concerning cosmic structure and its formation.
- Codes that perform this task are called *halo-finders*.

Cosmological N-body Simulations

The results of a cosmological simulation of 128^3 dark matter particles at redshift $z = 0$ with $H_0 = 70.4$ and density parameters $\Omega_m = 0.272$ and $\Omega_\Lambda = 0.728$. The box length corresponds to 88.8 Mpc.



Unbinding Particles

- By convention, it is customary to treat all particles assigned to a halo as bound to it, even though from a strict energetic perspective they may not be.
- For subhalos, on the other hand, it is vital to identify and remove unbound particles:
  - Subhalos are located within a host halo and therefore expected to be contaminated by the host's particles
  - Usually subhalos contain far less particles than their hosts, so assigning particles to it without an unbinding procedure can influence its physical properties significantly.
- "Removing a particle" means here to assign it to the parent structure. This applies recursively to any level of substructure within substructure.

Goals of this thesis

- `RAMSES` (Teyssier, R. 2002) is a N-body and hydrodynamical code that contains a clump finding algorithm, `PHEW` (Bleuler et al. 2015).
- Both `PHEW` and `RAMSES` are fully parallel and make use of the MPI library. `PHEW` works on-the-fly.
- The goal of this thesis is to implement a particle unbinding algorithm to work with `PHEW` that is also fully parallel and works on-the-fly.

PHEW

- `PHEW` groups cells together by separating the mass density field along minima, thus dividing the density field into patches.
- The algorithm can be divided in four main steps:
  - segmentation
  - connectivity establishment
  - noise removal and
  - substructure merging

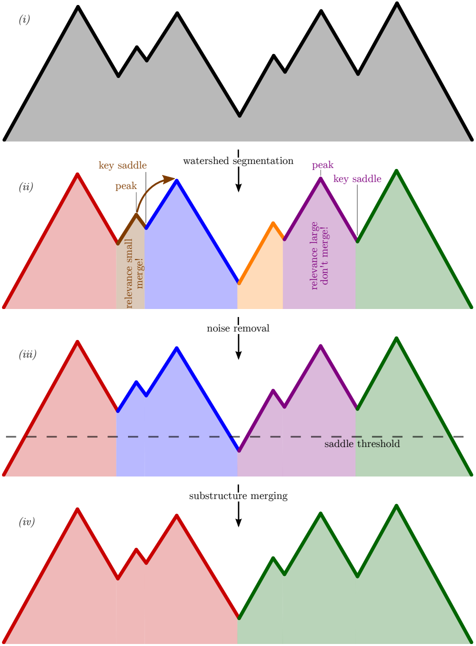
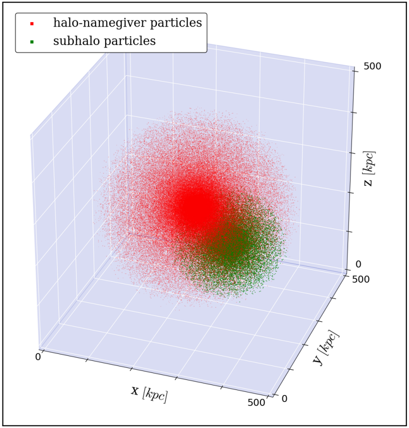


Image adapted from Bleuler et al. 2015.

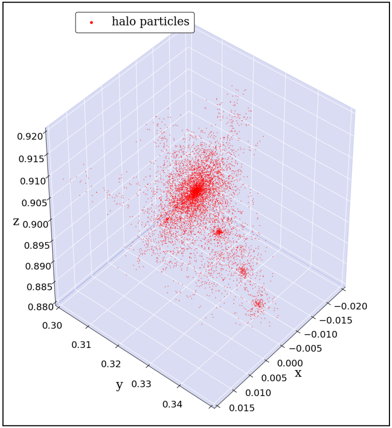
Test Cases

To demonstrate the effects of the particle unbinding, the following datasets will be used:

- `dice-twobody`-dataset: A highly idealistic structures where the effects can be seen and evaluated more easily, created using `DICE` (Perret 2016).
- `cosmo`-dataset: A halo from the previously shown cosmological simulation which is made up from 7030 particles.



The initial particle distribution of the dice-twobody dataset. A smaller halo (subhalo 1) made of 40'000 particles is nested within a bigger halo (halo-namegiver), which contains 200'000 particles.



cosmo-dataset: A halo as identified by PHEW of the previously shown cosmological simulation at redshift $z = 0$.

Particle Unbinding

In an isolated system in the centre of mass frame, each particle i can be assigned an energy E_i:

$$E_i = T_i + V_i = \frac{1}{2} m_i \cdot v_i^2 + m_i \phi(\vec{r}_i)$$

A particle is considered bound if:

$$E_i < 0 \quad \Leftrightarrow \quad v_i < \sqrt{-2 \cdot \phi(\vec{r}_i)}$$

Particle Unbinding

The only considered potential ϕ is the gravitational potential of the particles themselves. The potential is determined by the Poisson equation:

$$\Delta\phi = 4\pi G\rho$$

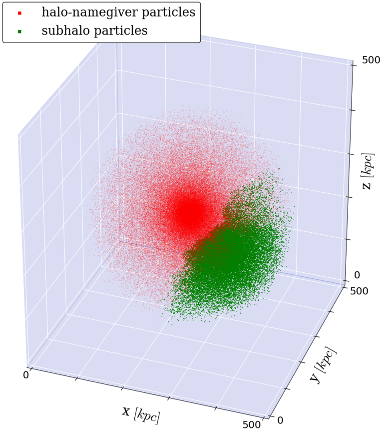
The spherically symmetric Poisson equation can be solved analytically for ϕ:

$$\phi(r_i) = -G \int_{r_i}^{r_{max}} \frac{M(<\tilde{r})}{\tilde{r}^2} \mathrm{d}\tilde{r} - G\frac{M_{tot}}{r_{max}}$$

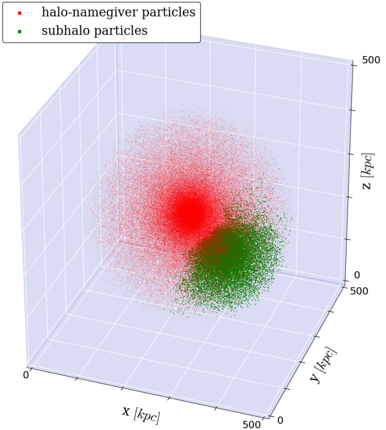
Where $M(<r) \equiv \int_0^r 4\pi\rho(\tilde{r})\tilde{r}^2 \mathrm{d}\tilde{r}$ is the mass enclosed by a sphere of radius r such that the clump's total mass is enclosed by the radius r_{max}: $M_{tot} = M(<r_{max})$ and G is the gravitational constant and ρ is the density.

Results: `dice-twobody-dataset`

PHEW only

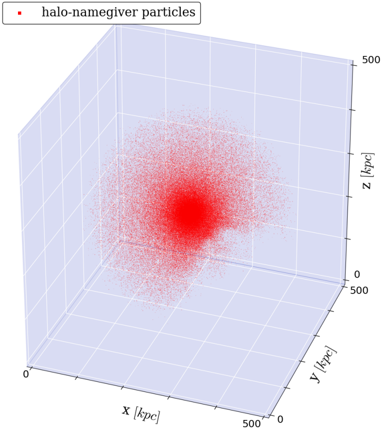


simple unbinding

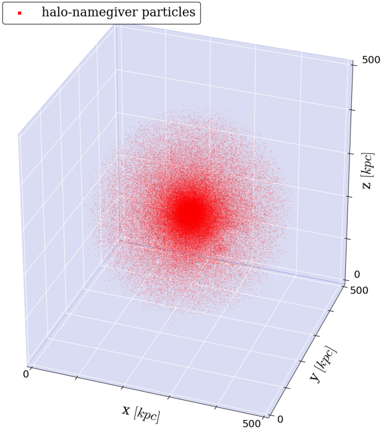


Results: `dice-twobody-dataset`: halo-namegiver particles only

PHEW only

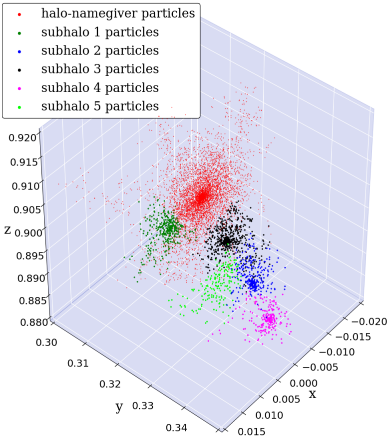


simple unbinding

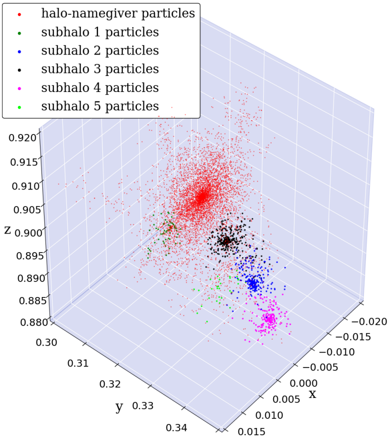


Results: `cosmo`-dataset: halo-namegiver particles only

PHEW only

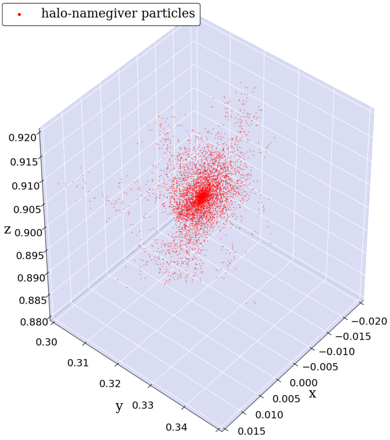


simple unbinding

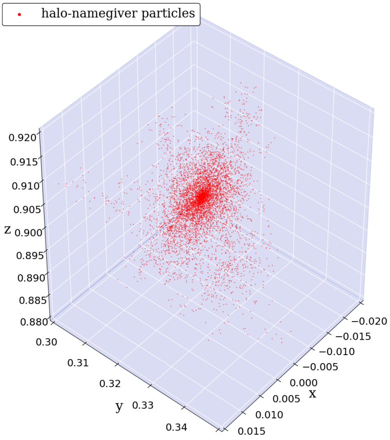


Results: `cosmo`-dataset: halo-namegiver particles only

PHEW only



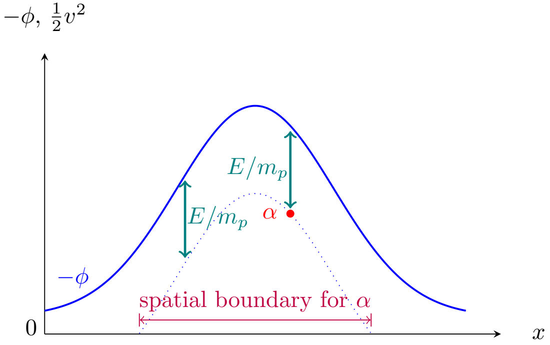
simple unbinding



Accounting for Neighbouring Structures

By construction, the identified subhalos are not isolated. This fact changes the situation significantly for the interpretation of what particles should be considered bound.

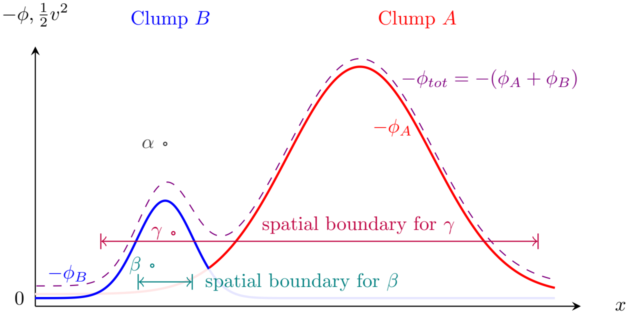
Consider first a particle α in the potential of an isolated clump:



The spatial boundaries of its trajectory can be found by demanding energy conservation $E/m_p = \frac{1}{2}v^2 + \phi = const.$ by following the curve of constant total energy to the points where $v^2 = 0$.

Accounting for Neighbouring Structures

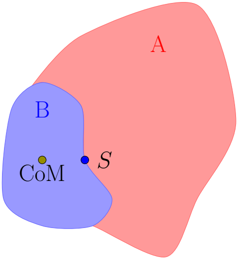
Now apply the same thoughts to an isolated halo that is made up from two clumps:



- α is clearly not bound to the clump B.
- β will remain bound on an elliptic trajectory around the centre of mass.
- γ is energetically bound to the clump just like β, but because of clump A's neighbouring potential, the particle can leave the boundaries of clump B and wander off deep into clump A.

Accounting for Neighbouring Structures

$\Rightarrow$ Particles like γ shouldn't be considered bound.
The reason γ can wander off is because its boundary extends past the interface that connects the two clumps
$\Rightarrow$ the condition for a particle to be *exclusively* bound must be that its trajectory must never reach that interface.

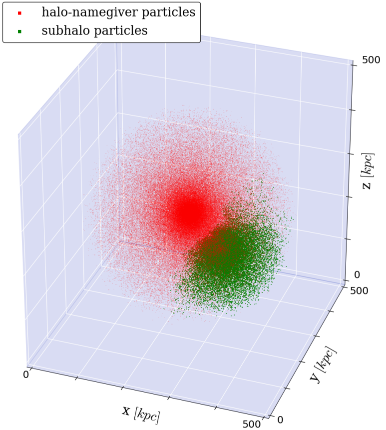


$\Rightarrow$ Define S to be the point on the interface to the neighbouring structure(s) that is closest to B's centre of mass and ϕ_S to be the potential of clump B at that point. Using the same argumentation as before, a particle can't reach S if

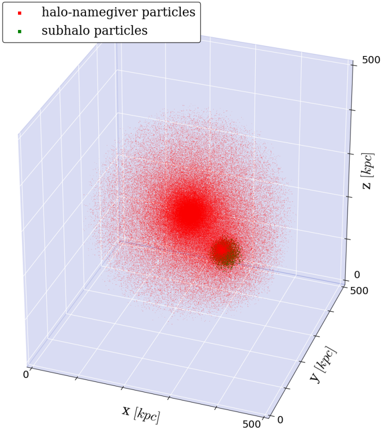
$$v < \sqrt{-2(\phi - \phi_S)}$$

Results: `dice-twobody-dataset`

simple unbinding

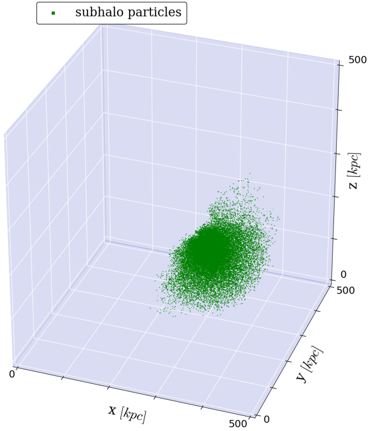


accounting for neighbours

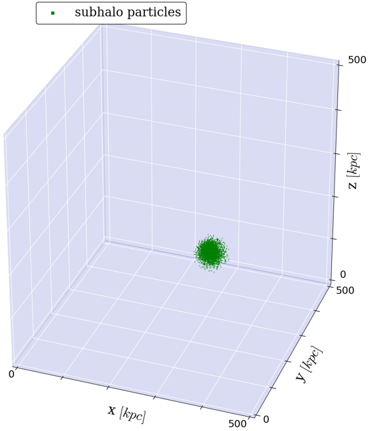


Results: `dice-twobody-dataset`: subhalo particles only

simple unbinding



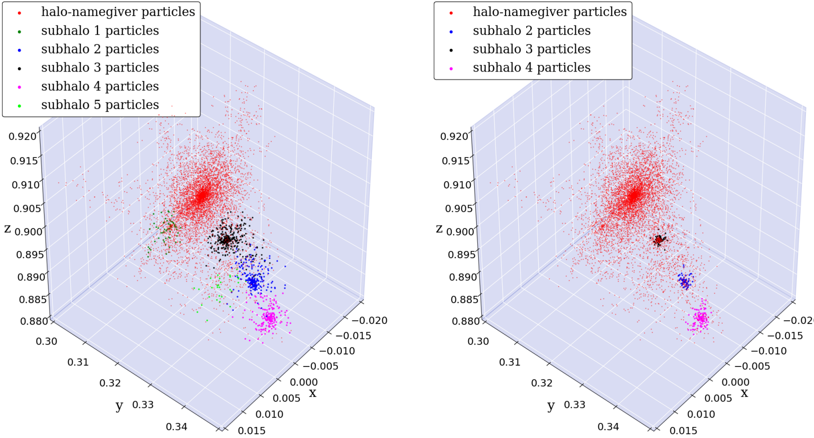
accounting for neighbours



Results: `cosmo`-dataset

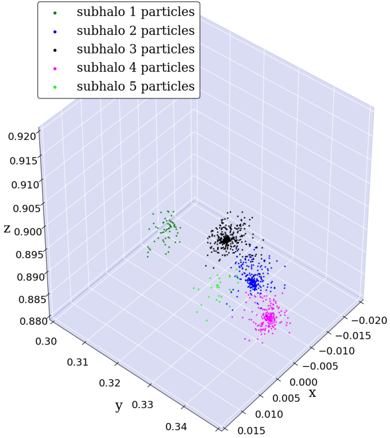
simple unbinding

accounting for neighbours

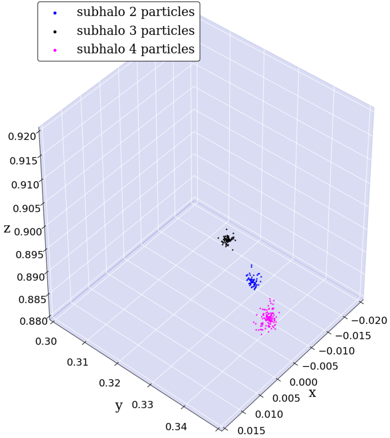


Results: `cosmo`-dataset: subhalo particles only

simple unbinding

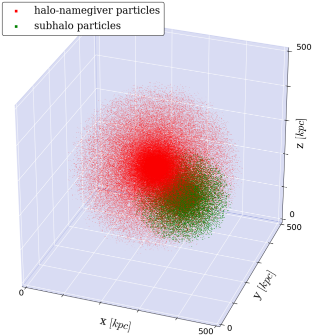


accounting for neighbours

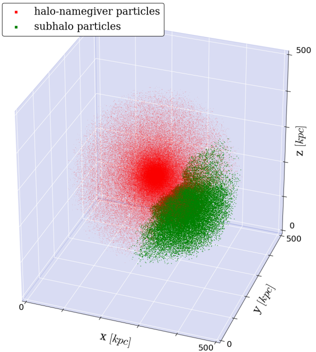


Biased Clump Properties

initial set-up



clumps found by `PHEW`



The identified clump properties will be biased:

- Missing particles: Subhalo is cut off
- Alien particles: Subhalo in contaminated by host's particles

Biased Clump Properties

It seems likely that the clump properties after particle unbinding should be closer to the known ones, particularly so if only exclusively bound particles are considered.

$\Rightarrow$ recompute the clump properties after unbinding and use this updated information to go through the entire procedure again. Reiterate until the bulk velocity of each clump converges:

$$\text{bulk velocity converged} \Leftrightarrow \left| \frac{v_{bulk,old} - v_{bulk,new}}{v_{bulk,old}} \right| < \varepsilon$$

where ε is a user-defined convergence limit.

Results: Converging of the bulk velocity for the `dice-twobody`-dataset

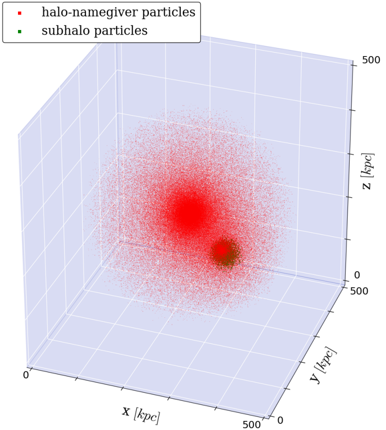
The deviation $D_{orig} = \left|\frac{v_{bulk} - v_{orig}}{v_{orig}}\right|$ from the originally set bulk velocity to the computed bulk velocity for the subhalo of the `dice-twobody`-dataset in dependence of the convergence limit ε:

ε	`niter`	D_{orig}
0.5	2	0.2326
0.1	4	0.0419
0.01	7	0.0024
0.001	8	0.0014
0.0001	10	0.0009

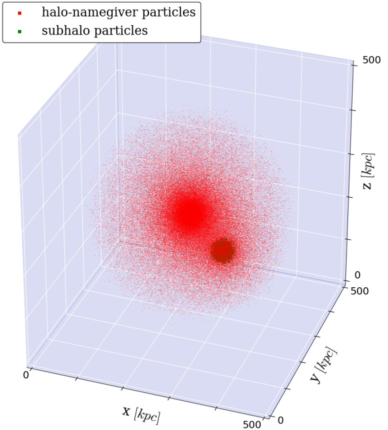
The bulk velocity computation needed `niter` iterations to converge.

Results: `dice-twobody-dataset`

accounting for neighbours

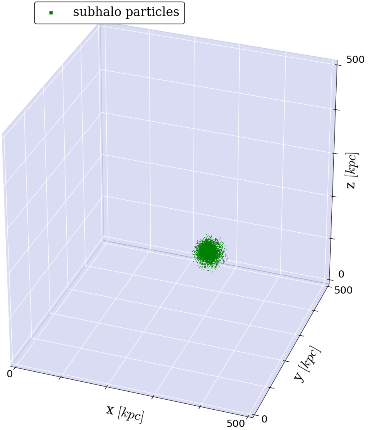


iterative properties determination

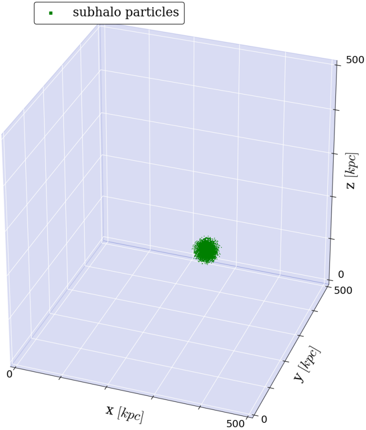


Results: `dice-twobody-dataset`: halo-namegiver particles only

accounting for neighbours

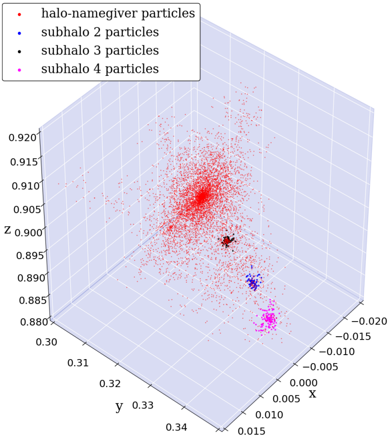


iterative properties determination

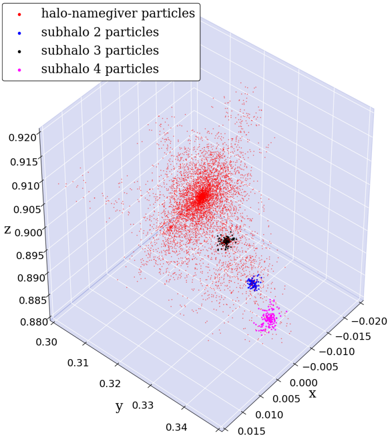


Results: `cosmo`-dataset: halo-namegiver particles only

accounting for neighbours

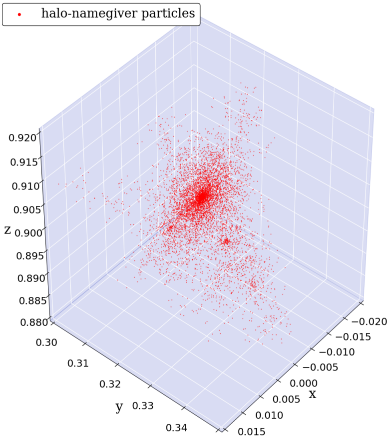


iterative properties determination

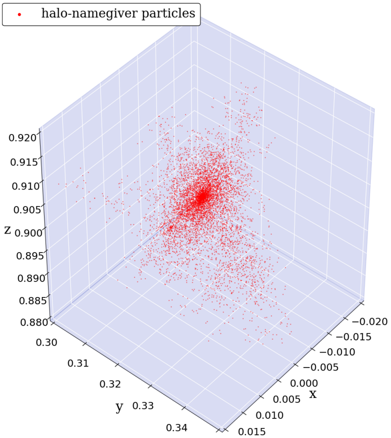


Results: `cosmo`-dataset: halo-namegiver particles only

accounting for neighbours



iterative properties determination



References

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